

CLAIMS

We claim:

1. An iterative method of normalized waveform inversion to obtain a model parameter describing one or more physical properties of a medium, the method comprising the steps of:
 - a) inputting a time domain measurement data set $D_{ji}^d(t)$, ($j = 1 \sim NG$; $i = 1 \sim NS$), where d denotes a data tensor, NG is the number of receivers and NS is the number of sources;
 - b) means for minimizing a model parameter m below an error bound in the process of creating a normalized waveform inversion, wherein said minimizing step further comprises:
 - i) Fourier transforming the time domain measurement data set $D_{ji}^d(t)$ to create a measurement spectral data set $D_{ji}^d(\omega)$;
 - ii) normalizing the measurement spectral data set $D_{ji}^d(\omega)$ to create a normalized data wavefield $T_{ji}^d(\omega)$;
 - iii) modeling a medium by iterating the model parameter m describing one or more physical properties of the medium; by
 - (1) minimizing a weighted error, between the normalized data wavefield $T_{ji}^d(\omega)$ and the normalized modeled wavefield $T_{ji}^m(\omega)$ of the response of the medium, to a level below the error bound;
 - (2) outputting the iterated model parameter m corresponding to the weighted error below the error bound, as a minimized model parameter.
2. In the modeling step of claim 1, the physical property is selected from the group comprising: a velocity of sound propagation, density, permeability, porosity, resistivity, permittivity, Young's modulus, a component of the tensorial stress-strain properties, shear modulus, amount of water present, and amount of oil present.

3. In the modeling step of claim 1, the error bound divided by an initial error E_0 is selected from the group consisting of: below 10^{-5} , below 10^{-6} , below 10^{-7} , and below 10^{-8} .
4. An iterative method of using normalized waveform inversion to obtain a model parameter describing one or more physical properties of a medium, the method comprising the steps of:
 - a) inputting one or more each of NS source and NG measurement spatial locations;
 - b) measuring time domain data at each of the NG measurement locations resulting from an input waveform at one of the NS source locations propagating through a medium,
 - i) for each of the NS source locations,
 - ii) thereby forming a time domain measurement data set

$$D_{ji}^d(t), \quad (j = 1 \sim NG; i = 1 \sim NS), \text{ where } d \text{ denotes a data tensor};$$
 - c) Fourier transforming the time domain measurement data set $D_{ji}^d(t)$ to create a measurement spectral data set $D_{ji}^d(\omega)$ having frequency and amplitude information for each of the NG measurement locations;
 - d) normalizing the measurement spectral data set $D_{ji}^d(\omega)$ to create a normalized data wavefield $T_{ji}^d(\omega)$;
 - e) modeling the medium using an iterated model parameter m describing one or more physical properties of the medium,
 - (1) the NS source and the NG measurement spatial locations used as respective model input and model response spatial locations contained within the model of the medium,
 - (2) and initializing the iterated model parameter m with corresponding one or more known bulk properties of the medium being modeled,
 - ii) said modeling step comprising:
 - iii) creating a measurement model by:
 - (1) applying a delta function source collocated with the i^{th} NS source,

- (2) modeling the response at the NG measurement locations, using a time domain modeling method, to create a synthetic medium response at the j^{th} receiver due to the i^{th} source, $\mathbf{P}_{ji}^m(t)$, m denoting the model response,
 - (3) repeating the applying and modeling steps at each of the NS source locations and NG measurement locations until the measurement model is full, and
 - iv) Fourier transforming the model response $\mathbf{P}_{ji}^m(t)$, to obtain a frequency domain synthetic response $\mathbf{P}_{ji}^m(\omega)$;
 - v) forming a normalized modeled wavefield using the frequency domain synthetic response $\mathbf{T}_{ji}^m(\omega) = \mathbf{P}_{ji}^m(\omega) [\mathbf{P}_{ii}^m(\omega)]^{-1}$; and
 - f) minimizing a weighted error, between the normalized data wavefield $\mathbf{T}_{ji}^d(\omega)$ and the normalized modeled wavefield $\mathbf{T}_{ji}^m(\omega)$ of the response of the medium, to a level below an error bound,
 - i) said weighted error met by using the iterated model parameter m , known as the a minimized model parameter m .
5. The method of claim 4 wherein the modeled normalized wavefield $\mathbf{T}_{ji}^m(\omega)$ is independent of the input waveform applied to any of the NS source locations.
 6. The method of claim 4 further comprising the step of:
 - a) storing the minimized model parameter m in a computer-readable medium.
 7. The method of claim 4 further comprising the steps of:
 - a) displaying the minimized model parameter m as a graphical representation of one or more of the physical properties of the medium measured,
 - b) storing an output image represented by the minimized model parameter m in a computer-readable medium.
 8. The method of claim 4 further comprising the step of;
 - a) storing as a computer program in at least one computer-readable medium,
 - b) said steps of claim 4.

9. The method of claim 4 wherein said weighted error results from a weighing matrix W_d that is an inverse of the standard deviation of the normalized data wavefield $T_{ji}^d(\omega)$.
10. The method of normalized waveform inversion of claim 9 wherein said minimizing step weighted error $\phi(m)$ is calculated by a root mean square of the weighing matrix W_d multiplied by the difference between the normalized data wavefield $T_{ji}^d(\omega)$ and the normalized modeled wavefield $T_{ji}^m(\omega)$, or $\phi(m) = \left\| W_d (T_{ji}^m(\omega) - T_{ji}^d(\omega)) \right\|^2$ summed over all frequencies, i sources, and j receivers.
11. The method of claim 4 wherein said normalization step is further comprised of the steps of:
 - a) choosing one of the measurement spectral data set $D_{ji}^d(\omega)$ at one of the measurement locations, such as $D_{li}^d(\omega)$,
 - (1) said chosen measurement spectral data set $D_{li}^d(\omega)$ known as a reference measurement;
 - ii) dividing the measurement spectral data set $D_{ji}^d(\omega)$ amplitude at a particular frequency in the measurement spectral data set $D_{ji}^d(\omega)$,
 - iii) by the amplitude of the reference measurement $D_{li}^d(\omega)$ at the same frequency,
 - b) to create a normalized data wavefield $T_{ji}^d(\omega)$.
12. The method of claim 4 wherein the error bound of the minimizing step is calculated by first assigning an initial error E_0 , then dividing each subsequent iterated error bound by the initial error E_0 .
13. An iterative method of using normalized waveform inversion to obtain a model parameter describing one or more physical properties of a medium, the method comprising the steps of:
 - a) inputting one or more each of NS source and NG measurement spatial locations;

- b) measuring time domain data at each of the NG measurement locations resulting from an input waveform at one of the NS source locations propagating through a medium,
 - i) for each of the NS source locations,
 - ii) thereby forming a time domain measurement data set

$$\mathbf{D}_{ji}^d(t), \quad (j = 1 \sim NG; i = 1 \sim NT), \text{ where } d \text{ denotes a data tensor;}$$
- c) Fourier transforming the time domain measurement data set $\mathbf{D}_{ji}^d(t)$ to create a measurement spectral data set $\mathbf{D}_{ji}^d(\omega)$ having frequency and amplitude information for each of the NG measurement locations;
- d) normalizing the measurement spectral data set $\mathbf{D}_{ji}^d(\omega)$ to create a normalized data wavefield $\mathbf{T}_{ji}^d(\omega)$;
- e) modeling the medium using an iterated model parameter \mathbf{m} describing one or more physical properties of the medium,
 - the NS source and the NG measurement spatial locations used as respective model input and model response spatial locations contained within the model of the medium,
 - and initializing the iterated model parameter \mathbf{m} with corresponding one or more known bulk properties of the medium being modeled,
 said modeling step comprising:
 - i) creating a measurement model by:
 - (1) applying a delta function source collocated with the i^{th} NS source,
 - (2) modeling the response at the NG measurement locations, using a time domain modeling method, to create a synthetic medium response at the j^{th} receiver due to the i^{th} source, $\mathbf{P}_{ji}^m(t)$, \mathbf{m} denoting the model response,
 - (3) repeating the applying and modeling steps at each of the NS source locations and NG measurement locations until the measurement model is full, and
 - ii) Fourier transforming the model response $\mathbf{P}_{ji}^m(t)$, to obtain a frequency domain synthetic response $\mathbf{P}_{ji}^m(\omega)$;

iii) forming a normalized modeled wavefield using the frequency domain

synthetic response $\mathbf{T}_{ji}^m(\omega) = \mathbf{P}_{ji}^m(\omega) [\mathbf{P}_{li}^m(\omega)]^{-1}$; and

- f) minimizing a weighted error, between the normalized data wavefield $\mathbf{T}_{ji}^d(\omega)$ and the normalized modeled wavefield $\mathbf{T}_{ji}^m(\omega)$ of the response of the medium, to a level below an error bound,
- g) said weighted error met by using the iterated model parameter \mathbf{m} , known as the a minimized model parameter \mathbf{m} .

14. The method of claim 13 further comprising the step of;

- a) storing as a computer program in at least one computer-readable medium,
i) said steps of claim 13.

15. An article of manufacture for normalized waveform inversion using a computer, said article comprising:

a computer readable medium comprising instructions for a computer to execute, said execution comprising the steps of:

- a) inputting one or more each of NS source and NG measurement spatial locations;
b) measuring time domain data at each of the NG measurement locations resulting from an input waveform at one of the NS source locations propagating through a medium,
i) for each of the NS source locations,
ii) thereby forming a time domain measurement data set

$\mathbf{D}_{ji}^d(t)$, ($j = 1 \sim NG$; $i = 1 \sim NS$), where d denotes a data tensor;

- c) Fourier transforming the time domain measurement data set $\mathbf{D}_{ji}^d(t)$ to create a measurement spectral data set $\mathbf{D}_{ji}^d(\omega)$ having frequency and amplitude information for each of the NG measurement locations;
d) normalizing the measurement spectral data set $\mathbf{D}_{ji}^d(\omega)$ to create a normalized data wavefield $\mathbf{T}_{ji}^d(\omega)$;

- e) modeling the medium using an iterated model parameter m describing one or more physical properties of the medium,
- the NS source and the NG measurement spatial locations used as respective model input and model response spatial locations contained within the model of the medium,
- and initializing the iterated model parameter m with corresponding one or more known bulk properties of the medium being modeled,
- said modeling step comprising:
- i) creating a measurement model by:
 - (1) applying a delta function source collocated with the i^{th} NS source,
 - (2) modeling the response at the NG measurement locations, using a time domain modeling method, to create a synthetic medium response at the j^{th} receiver due to the i^{th} source, $P_{ji}^m(t)$, m denoting the model response,
 - (3) repeating the applying and modeling steps at each of the NS source locations and NG measurement locations until the measurement model is full, and
 - ii) Fourier transforming the model response $P_{ji}^m(t)$, to obtain a frequency domain synthetic response $P_{ji}^m(\omega)$;
 - iii) forming a normalized modeled wavefield using the frequency domain synthetic response $T_{ji}^m(\omega) = P_{ji}^m(\omega) [P_{ii}^m(\omega)]^{-1}$; and
- f) minimizing a weighted error, between the normalized data wavefield $T_{ji}^d(\omega)$ and the normalized modeled wavefield $T_{ji}^m(\omega)$ of the response of the medium, to a level below an error bound,
- i) said weighted error met by using the iterated model parameter m , known as the a minimized model parameter m .

16. An iterative method of using normalized waveform inversion to obtain a model parameter describing one or more physical properties of a medium, the method comprising the steps of:

- a) inputting one or more each of NS source and NG measurement spatial locations;
- b) measuring time domain data at each of the NG measurement locations resulting from an input waveform at one of the NS source locations propagating through a medium,
 - i) for each of the NS source locations,
 - ii) thereby forming a time domain measurement data set

$$D_{ji}^d(t), \quad (j = 1 \sim NG; i = 1 \sim NS), \text{ where } d \text{ denotes a data tensor};$$
- c) Fourier transforming the time domain measurement data set $D_{ji}^d(t)$ to create a measurement spectral data set $D_{ji}^d(\omega)$ having frequency and amplitude information for each of the NG measurement locations;
- d) normalizing the measurement spectral data set $D_{ji}^d(\omega)$ to create a normalized data wavefield $T_{ji}^d(\omega)$;
- e) modeling the medium using an iterated model parameter m describing one or more physical properties of the medium,

the NS source and the NG measurement spatial locations used as respective model input and model response spatial locations contained within the model of the medium,

and initializing the iterated model parameter m with corresponding one or more known bulk properties of the medium being modeled,

said modeling step comprising:

 - i) creating a measurement model by:
 - (1) applying a delta function source collocated with the i^{th} source,
 - (2) modeling the response at the NG measurement locations, using a frequency domain modeling method, to create a **frequency domain** synthetic response at the j^{th} receiver due to the i^{th} source, $P_{ji}^m(\omega)$, m denoting the model response,
 - (3) repeating the applying and modeling steps at each of the NS source locations and NG measurement locations until the frequency domain synthetic response is full, and

- ii) forming a normalized modeled wavefield using the frequency domain synthetic response $\mathbf{T}_{ji}^m(\omega) = \mathbf{P}_{ji}^m(\omega) [\mathbf{P}_{ii}^m(\omega)]^{-1}$; and
 - f) minimizing a weighted error, between the normalized data wavefield $\mathbf{T}_{ji}^d(\omega)$ and the normalized modeled wavefield $\mathbf{T}_{ji}^m(\omega)$ of the response of the medium, to a level below an error bound,
 - i) said weighted error met by using the iterated model parameter m , known as the a minimized model parameter m .
17. The method of claim 16 further comprising the step of;
- a) storing as a computer program in at least one computer-readable medium, said steps of claim 16.
18. An article of manufacture for normalized waveform inversion using a computer, said article comprising: a computer readable medium comprising instructions for a computer to execute, said execution comprising the steps of claim 16.